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Relative influence of urban-development strategies and water management on mixed (separated and combined) sewer overflows in the context of climate change and population growth: A case study in Nantes

Valérie Mahaut[a,*], Hervé Andrieu[b]

[a] École d'architecture, Faculté de l'aménagement, Université de Montréal, C.P. 6128, succursale Centre-ville, Montréal, Québec, H3C 3J7, Canada
[b] Department of Geotechnical Engineering, Environment and Risks, IFSTTAR, Institut de Recherche en Sciences et Techniques de la Ville, IRSTV – FR CNRS 2488, Route de Bouaye CS4, 44344, Bouguenais Cedex, Nantes, France

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ABSTRACT

This paper explores the link between urban planning and hydrological mechanisms. Using a hydrological model, it assesses the relative influence of different urban-development and water-management modes on sewer-system overflows. It combines and compares the impacts of three climate change scenarios going up to 2100, which take into account the implementation of various urban-development strategies, as well as two demographic scenarios. Using this method, the study weighs the importance of the different hydrological mechanisms at play and proposes land-development strategies to implement with regards to climate change and population.

The city of Nantes, the hydraulic network of which is well documented, serves as a case study. The results show that, in Nantes, climate change might have a smaller impact on overflows than population growth and urban development in certain scenarios. To limit overflows, insofar as there is no change in water use, this study suggests densifying existing urban areas served by a separative sewer system. It also provides a comparative appraisal of common and alternative water-management practices to reduce overflow.

Simulations of different scenarios can help to foster a better understanding of the relationship between urban management and hydrological mechanisms.

1. Introduction

Water is probably the natural element on Earth that is the most exposed to the impacts of climate change (CC). Much research has thus been done to assess the impacts of CC on hydrological disorders. Studies have generally focused on one specific topic corresponding to a problem related to water. These problems can be categorized into three main types (Kundzewicz & Kowalczak, 2009): "too much" (floods, overflowing), "too little" (water supply in terms of quantity; scarcity; decrease in river flow; increase in demand for water for domestic consumption; recreational use or irrigation) or "too dirty" (pollution of watercourses; water supply in terms of quality; infection risks; decrease in biodiversity). These issues are accentuated in urban areas where urbanization heavily modifies natural cycles, infrastructures are rigid and ageing, and a large number of people per unit area are affected (Wagner & Breil, 2013). Since hydrological disorders are extremely harmful to both human society and the environment and could be aggravated by increasing urbanization and potentially by climate change (CC) as well (IPCC, 2012), studies combining the impacts of both of these factors are crucial to understanding how to manage urban areas to reduce the negative impacts of water within them.

In the category of problems related to "too much" water, Olsson, Berggren, Olofsson, and Viklander, (2008); Jung, Chang, and Moradkhani, (2010), and Huong and Pathirana (2013) analyze the evolution of flood risk in urban zones and point towards urban planning as the main factor at play in terms of flooding, combined with sea-level rise depending on the case study. More specifically, within this category of research, the evolution of urban-sewer networks is also assessed over time. Denault, Millar, and Lence, (2006); Mailhot and Duchesne (2010), and Forsee and Ahmad (2011) analyze the impacts of CC and changes in land use on design peak flow in order to assess the future capacity of drainage infrastructure. This was followed by studies evaluating the behavior of the sewer system in terms of floods, overflowing, and manhole flooding, such as Nie, Lindholm, Lindholm, and Syversen, (2009); Nilsen, Lier, Bjerkholt, and Lindholm, (2011); Krieger, Kuchenbecker, Hüffmeyer, and Verworn, (2013); Mikovits et al. (2015).

* Corresponding author.
E-mail addresses: valerie.mahaut@hotmail.com (V. Mahaut), herve.andrieu@ifsttar.fr (H. Andrieu).

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As a potential solution to floods or overflows, local strategies and devices for water management are emerging, such as low impact development (LID) (Pyke et al., 2011), sustainable urban drainage systems (SUDS) (Semadeni-Davies, 2012), best management practices (BMP), rain gardens (RG) (Autixier et al., 2014) or rainwater harvesting (RWH) (Tavakol-Davani, Goharian, Hansen, & Hassan, 2016). The aforementioned studies have used CC scenarios to show the effectiveness of these strategies and devices in dealing with runoff. Semadeni-Davies, Hernebring, Svensson, and Gustafsson, (2008), and Tavakoli, De Smedt, Vansteenkiste, and Willems, (2014) examine the impact of CC on urban storm-water runoff, which would provoke changes in the flow rates of suburban watercourses that could cause flooding in residential areas.

Problems relating to "too little" water mainly concern water supply. Studies assessing the impact of CC on water supplies are wide ranging and cover both their quantity and quality (Astaraie-Imani, Kapelan, Fu, & Butler, 2012; Díaz, Stanek, Frantzeskaki, & Yeh, 2016; Kingsborough, Borgomeo, & Hall, 2016; Praskievicz & Chang, 2009, 2011). Most of the research on floods that examine high-flow conditions in rivers also analyze low-flow conditions as another hydrological extreme (Tavakoli et al., 2014; Xu & Luo, 2015; Hoang et al., 2016). Wu, Thompson, Kolka, Franz, and Stewart, (2013) and Chawla and Mujumdar (2015) focus their research on the flow regime of rivers. More specific subjects relating to problems of "too little" water are also examined using CC scenarios: for example, Teshager, Gassman, Schoof, and Secchi, (2016) and Fader, Shi, von Bloh, Bondeau, and Cramer, (2016) analyze agricultural irrigation, and the study by Liu, Tang, Voisin, and Cui, (2016) focuses on hydroelectrical potential. While a large majority of studies analyze the impact of CC on the water supply, a few assess the impact of CC on water demand and modifications in habits of water use. (Eslamian, Li, & Haghighat, 2016; Grouillet, Fabre, Ruelland, & Dezetter, 2015; Parandvash & Chang, 2016).

The problem of water that is "too dirty" has been directly analyzed by Sterk, de Man, Schijven, de Nijs, and de Roda Husman, (2016); their paper explores the impact of CC on risk infection for those bathing downstream from wastewater overflows and water treatment plants. Studies dealing with sewer overflows (Abdellatif, Atherton, Alkhaddar, & Osman, 2015; Bendel, Beck, & Dittmer, 2013; Krieger et al., 2013; Langeveld, Schilperoort, & Weijers, 2013; Nie et al., 2009; Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008; Wu et al., 2013; Tavakol-Davani et al., 2016), the topic of this paper, are indirectly related to the problem of water that is "too dirty", but it is not their primary focus. Those studies focus more on assessing the evolution of overflows in combined sewer systems using CC scenarios. They make the hypothesis that increased overflows lead to increased pollution of watercourses (Lau, Butler, & Schütze, 2002). Combined sewer overflows (CSOs) are a mixture of untreated sewage and rainwater.

Although these studies offer interesting results that can inform management decision-making, few of them explain the connection between hydrological processes and urban-management strategies or, more precisely, comparatively analyze different urban-development methods and their potential to mitigate the studied phenomenon.

Indeed, once established, the infrastructures created through urban development are not subject to change for years, or even tens or hundreds of years, and are not very conducive to adaptation. With regards to floods and overflowing, urban planners have to adapt their water-management plans (Bell, 2015; Kingsborough et al., 2016; Stroch & Downes, 2011). Strategies to separate rainwater and wastewater, as well LID techniques and SUDS, are increasingly implemented. Studies assessing the effects of RWH on water management within the context of CC present a partial technical response to CC at the scale of the city and its surroundings. But other changes in urban development, technical solutions, or strategies to reduce water use could be used to mitigate the impact of CC.

As a result, in the context of CC and demographic pressure on cities, a better understanding is needed of the relative impacts of (1) the variable factors in future developments (population density, impervious areas, sewer-system mode) and (2) changes in water use (reuse of water, reducing consumption; rainwater-management devices such as RWH, LID, SUDS, RG or BMP; reducing impervious areas; dry toilets; local treatment processes).

This research thus proposes a more comprehensive and comparative approach to assess solutions to hydrological disorders in terms of land management.

Beyond the direct interest of analyzing the performance of Nantes's sewer system under the pressures of CC and urbanization, this study also indirectly offers two original elements: (1) the transcription of the hydrological formula of the model used in terms of the variables related to the modes of land development, and (2) a description and explanation of the interrelationships between hydrological mechanisms and management modes.

2. Background

In order to obtain its objective, this study aims to assess the long term hydrological behavior of overflows of untreated wastewater from Nantes's sewer system. The method combines CC, demographic, and urban-development scenarios over one century. Using a hydrological model, the evolution of each variable according to future scenarios provided information about the hydrological mechanisms involved, which allowed us to analyze the potential of different development strategies that could be implemented. In this case study, overflows can be frequent and contribute to polluting the natural environment (Lau et al., 2002). When the water table is high in Nantes, mostly during the winter, wastewater overflow can occur even when there is little or no rain. This is because of the extraneous water that overloads the system and exacerbates wastewater overflow. These episodes of sewer network overload, which happen especially during the winter or long or intense rain events, reduce the transportation capacity of networks and increase the frequency and volume of network overflow (Ashley et al., 2007). The resulting nonpoint source pollution gradually degrades the environment. In this case study, overflows of wastewater into the environment reached nearly ten per cent of the total volume that flows at the outlet of the territory per year. The pollution caused by this phenomenon is thus far from negligible. The effects of nonpoint source pollution are often underestimated by the general public, politicians, and the media. This is probably because they are not as spectacular as intense weather events or disasters, like floods for example, which are easier to publicize.

This paper focuses on the conclusions of the research with regard to urban design. The hydrological modelling calculates the daily total transfer flow of the territory according to daily rainfall and potential evapotranspiration, and uses this data to project daily overflow volumes of the sewer systems into the environment. Using the model to analyze different CC and urban-development scenarios allows us to assess their potential impacts on system overflows. The results of this analysis will be compared and discussed in this paper with a special focus on facilitating the decision-making process in the elaboration of water-management plans for more sustainable development practices in cities. The method used in this research aims to develop a common understanding between engineers and land managers, whose occupations appear to have diverged a century ago. This reveals that there is a need to further investigate the links between the impact assessment of CC and future urban planning. It reveals a gap in the research, which this study begins to fill, on the links between hydrological processes and urban-design typology.

3. Case study

Nantes is situated at the beginning of the Loire Estuary in France. The Erdre River flows from the north through the city's historical center (Fig. 1) to the Loire River. In the interwar period, the Erdre was diverted toward the Loire through an underground canal controlled by

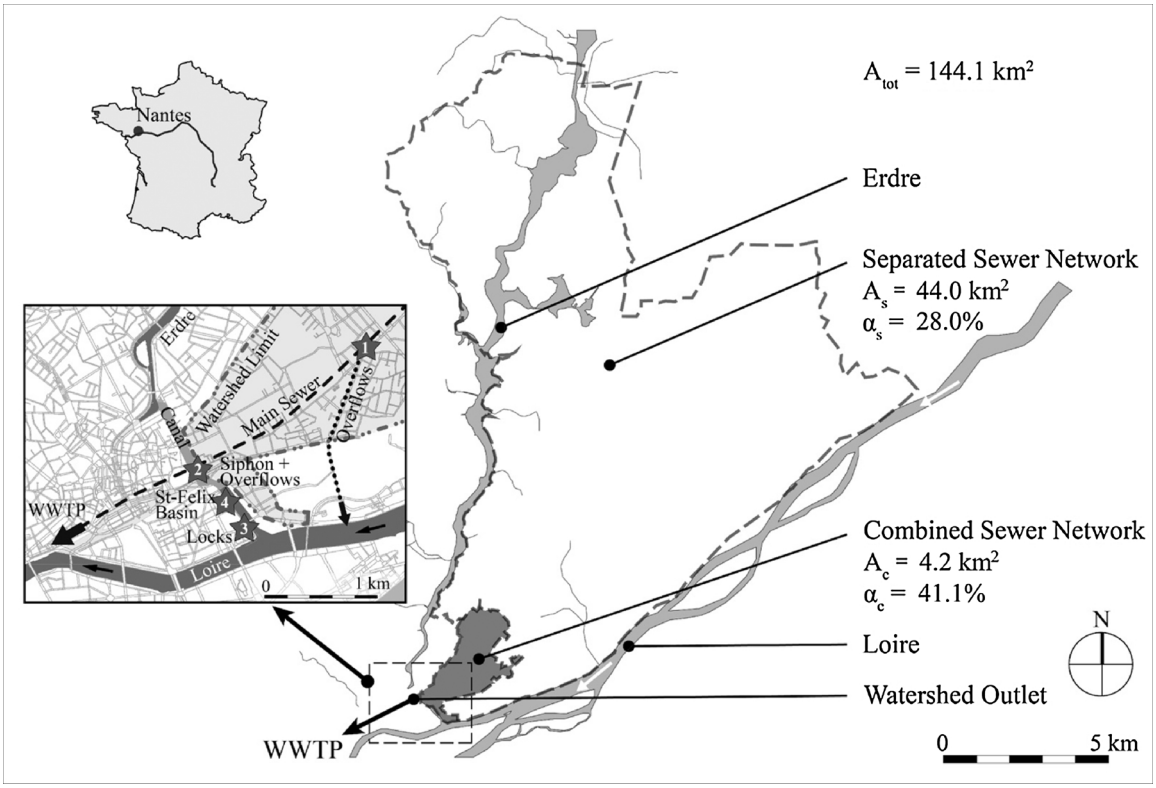


Fig. 1. Territory of Nantes-Metropole served by the sewer system under analysis, with its outlet next to the Erdre Canal. The frame shows Nantes city center with the location of the main sewer, upstream overflow weir (1), siphons (2), locks (3) and Saint-Félix Basin (4).

locks just before joining the Loire River (see the frame in Fig. 1). Upstream from the lock is a basin with a small boating harbor called the Saint-Félix Basin.

The main sewer that discharges wastewater from the studied sewer territory crosses the underground canal using a siphon system (Fig. 2). There are several overflow weirs in the sewer territory. One weir is situated a few kilometers upstream from the sewer outlet (black star number 1 in Fig. 1). Two other weirs are located at either end the siphon system (black star number 2 in Fig. 1). These weirs record overflow from the sewer network into the environment, into the Loire River in the first case and the Erdre River in the second. Wastewater that has not overflowed continues downstream to the wastewater treatment plant beyond the outlet of the studied sewer territory.

The canal is thus polluted by sewer overflows both before and after the siphon, and this pollution flows into the Saint-Félix Basin downstream. An emergency water intake was installed in the basin to provide Nantes with drinking water when the water level of the Loire, where the city's normal intake is located, falls below normal levels. And yet this emergency intake point is polluted by sewer-system overflow. This situation is not only harmful to the natural environment, but is also particularly dangerous to the community in the event that Nantes needs to use its emergency water intake.

The territory served by this main sewer collects wastewater (sewage) from the city, the suburbs, and a few villages to the north (Fig. 1), as well as rainwater from the city center (Fig. 3). It covers 144 km^2 of land used for various purposes (urban; suburban, and industrial areas; agricultural land; pastures; marshlands; and wetlands).

A small area of the territory, close to the city center, is equipped with a combined sewer system (CSS), which collects rainwater and

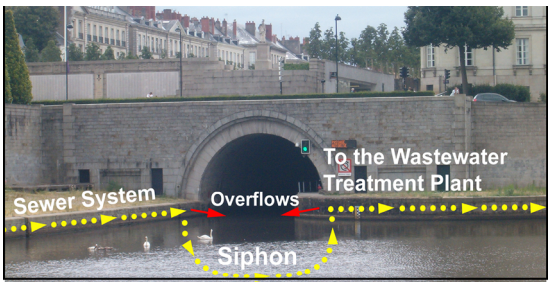


Fig. 2. The siphon and its overflow system, which allows the main sewer to transport wastewater under the Erdre Canal.

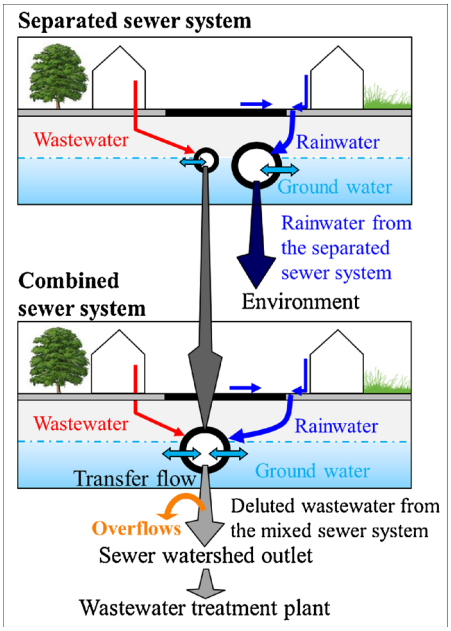


Fig. 3. Organization of the sewer-system studied.

wastewater (dark grey area, Fig. 1). This zone covers an area of 4.2 km^2 (A_c), and has an imperviousness coefficient of 41.1% (α_c). The vast majority of the territory (the remaining 140 km^2) uses a separate sewer system (SSS). The main sewer of the present case study only collects wastewater from this zone and does not collect the rainwater, which is discharged in several watercourses. Nevertheless, infiltration of water occurs through defects or cracks in the sewer pipes, which drain groundwater. This process can represent significant daily water volumes, which vary according to the season and the weather conditions (Belhadj, Joannis, & Raibault, 1995). Finally, a surface area of 44 km^2 (A_s) of the SSS territory is taken into account. A_s represents the part of the SSS territory located at a distance less than 100 m from the wastewater network. This surface area likely contributes to the drainage of soil water by the wastewater network. Its imperviousness coefficient is $\alpha_s = 28\%$.

Six years of daily data (2004–2009) are available to analyse and model the behavior of this hydrological system. This data set regroups: daily rainfall measured at the weather station, located 10 km southwest of the city center; potential evapotranspiration for Nantes calculated by the national weather service; total daily outflow from this territory, which includes both the CSS and the SSS zones; and daily overflow volume. The flow measurements are provided by the authorities in charge of managing the sewer system. During this period, the maximum daily rainfall is 40.4 mm (21 May 2005), with a total outflow of 101,000 m^3, and an overflow volume of 61,000 m^3. It must be noted that overflowing occurs very frequently. The median value of overflows is 2200 m^3. Overflowing occurs on about 69% of winter days (from November to April) and 30% of summer days (from May to October). As the percentage of rainy days is much lower (29% with rainfall over 1 mm), it shows that the drainage of groundwater by the wastewater network is a major factor contributing to the frequency of overflowing, mostly because of the very large surface covered by the wastewater system.

4. Methods

The objective of this study is to assess the relative influence of different urban-development and CC scenarios on wastewater overflows. It requires a hydrological model able: i) to simulate the response of the territory regrouping the CSS and SSS zones to atmosphere forcing, ii) to consider land use evolution associated with urban development. As the outputs (rainfall and potential evapotranspiration) of climate models are available at a daily time step, this time step has been retained for the hydrological model. A daily time step is not fully adapted to simulating the detailed response of urban watersheds to rainfall forcing, and the functioning of overflow devices. Nevertheless, this choice allows us to avoid disaggregating climatic model outputs, which is a complicated and sometimes speculative task.

4.1. The hydrological model

The total outflow from the considered territory is expressed as such:

$$Q = Q_r + Q_d + Q_w \quad (1)$$

with Q representing total outflow, Q_r runoff water outflow on CSS zone, Q_d soil drainage outflow of the total territory, and Q_w wastewater flow.

The wastewater flow (Q_w) is assumed as a daily constant equal to the base flow at the outlet of the combined sewer network during the dry season.

The runoff water outflow Q_r at CSS outlet is expressed as such:

$$Q_{r\,k} = C_c\, A_c\, Rn_k \quad (2)$$

with index k representing the day, Rn_k the net rainfall total during the day k, L_k (mm) the initial losses, A_c the surface area of the territory served by the CSS, and C_c the runoff coefficient and model parameter, which are usually lower than the imperviousness coefficient.

The net rainfall is the rainfall, minus the initial losses, which regroups depression storage and wetting of urban surfaces. It becomes positive when the reservoir representing initial losses is filled:

$$L_k = L_{k-1} + R_k - \frac{L_{k-1}}{L_{max}} PET_k$$

$$if\ L_k \le L_{max} \ => \ Rn_k = 0.0$$

$$if\ L_k > L_{max} \ => \ Rn_k = L_k - L_{max}\ and\ L_k = L_{max}$$

L_k is the water content (in m) of a reservoir, representing the initial losses on impervious surfaces of CSS, $Rn_k\ (m)$is the net rainfall, and $PET_k\ (m)$ is the potential evapotranspiration. The maximum capacity of this reservoir, L_{max} (m) is a model parameter.

Q_d is caused by the infiltration of groundwater into the non-waterproof pipes of: i) the combined sewer network (CSS), and ii) the wastewater sewer network of SSS. The modelling of the groundwater drainage by waste water sewer networks has been explored by Belhadj et al. (1995); Raynaud, Joannis, Schoefs, and Billard, (2008), and Raynaud (2009). These authors have developed conceptual models based on several reservoirs, which introduce a significant number of parameters. After testing a three-reservoir model inspired by these authors, in the end we retained a simple and robust non-linear reservoir model to represent the drainage of subsurface groundwater by the sewer network. Indeed, the two tested models have a high level of accuracy, whereas the model parameters are less numerous for the one-reservoir model. This paper neither presents the three-reservoir model, nor compares it with other model. The one-reservoir model adopted is a very simple application of the conceptual modeling framework proposed detailed by Fenicia, Kavetski, and Savenije, (2011). This reservoir is fed by rainfall falling on the pervious surfaces areas of the CSS + SSS zones. The flow contribution of this reservoir is expressed as such:

$$Q_{d\,k} = \alpha\, A_d\, [S_{k-1}]^{\beta} \quad (3)$$

with $Q_{d\,k}$ representing soil drainage flow during the time step k, S_{k-1} (mm) the level of water in the soil reservoir at the end of time step (k-1), δ the influence zone of the waste water network acting as a drain, and A_d the surface area which contributes to the soil reservoir $A_d = (1-C_c)A_c + (1-\alpha_s)A_s$, with A_s and c_s representing surface area and imperviousness coefficients of the territories served by the CSS and the SSS respectively. δ is a model parameter that controls the part of the total territory drained by the sewer network. An influence distance of the sewer network of 100 m has been retained a priori and this value must be adapted to the observed data.

The temporal evolution of the soil reservoir is expressed as follows:

$$S_k = Min\ (S_{k-1} + R_k - Q_{d\,k}/A_d - \frac{S_{k-1}}{S_{max}} PET_k\ ,\ S_{max}) \quad (4)$$

with S_k and S_{k-1}representing the levels of water in the soil reservoir at the end of time steps k and k-1 respectively, $S_{max}$the maximum level of the soil reservoir (equivalent to a saturated soil), R_k the rainfall during the time step k, and PET_k the potential evapotranspiration during the time step k ·It is assumed that the actual evapotranspiration is a proportion of the potential evapotranspiration equal to the filling rate of the soil reservoir.

Lastly, this model introduces six parameters that must be calibrated: L_{max}, C_c, S_{max}, α, β, $and\ \delta$. They are calibrated by comparing the observed daily flows to the modelled ones. The model performance is assessed by three classical criteria: Nash (Nash & Sutcliffe, 1970), represented as E, relative error, represented as RE, and correlation coefficient (r). The criteria E and RE are expressed such as:

$$E = 1 - \frac{\sum_{k=1}^{k=n} [Q_{mod\,i} - Q_{obs\,i}]^2}{\sum_{k=1}^{k=n} [Q_{obs\,i} - \bar{Q_{obs}}]^2}\ and\ RE = \frac{\sum_{k=1}^{k=n} [Q_{mod\,i} - Q_{obs\,i}]}{\sum_{k=1}^{k=n} Q_{obs\,i}} \quad (5)$$

with n representing the number of points of the outflow series, $Q_{obs\,i}$ and $Q_{mod\,i}$ the observed and modeled outflows at the i-th day respectively,

and Q_{obs} the mean value of the observed outflows.

The value of $Q_w$is set at 16,900 $m^3$from the analysis of the measured flow series, and the model calibration leads to the following parameter values: $L_{max} = 1.6\,10^{-3}m$, $C_c = 0.36$, $S_{max} = 8.0\,10^{-3}mm$, $\alpha = 0.022$, $\beta = 1.0$,and $\delta = 0.50$. For these parameter values, the criteria are $E = 0.65$, $RE = 0.03$, a nd r = 0.82, which represents acceptable values for a hydrological model applied to a time series of atmosphere forcing. It should be noticed that the value $\delta = 0.50$might indicate that the influence distance for the sewers that drain the soil is about 50 m. According to the model results, the mean flow at an annual scale is 30,984 m^3/day, which breaks down as follows: 52.5% for the waste water, 8% for the runoff of rainwater at the CSS outlet, and 37.5% of soil drainage water for the total territory (CSS + SSS). Even though proportions remain indicative, the proportion of soil drainage water could appear important compared to runoff water. It must kept in mind that it represents the drainage of a very large zone (48.2 km^2) by a wastewater system of a total length exceeding 250 km. Expressed differently, the soil drainage lies in the range of 45 m^3/day per kilometre of network.

$$Qdev_{\,m} = 0.000006341\,Q_m^2 - 0.12852\,Q_m \quad (6)$$

In this equation, $Qdev_{\,m}$ represents the mean monthly overflow and Q_m represents mean monthly outflow. The coefficient of correlation of the empirical relation is 0.82, a quite significant value.

4.2. The overflow model

The analysis of the data series of daily outflows and overflows shows a significant scattering, which confirms that it is not possible to accurately deduce daily overflows from daily outflows. It is illustrated by Fig. 4, which represents the percentage of overflows that have been observed for a given total outflow. It can be seen that overflows never occur for a total daily outflow of less than 21,500 m^3/d, and that 100% of the daily outflows exceeding 43,000 m^3/d come with overflows. In between these interval limits, the proportion of overflows increases when the outflow increases, which is logical.

Hopefully, an empirical relationship between outflows and overflows will clearly emerge by increasing the time step. In the end, a monthly time step has been retained to propose an empirical relationship between these two variables, as shown in Fig. 5. This empirical relationship is expressed as follows:

$$Qm_{\,dev} = 0.000006314\,Qm^2 - 0.12852\,Qm$$

In this equation, $Qm_{\,dev}$ represents monthly overflow and Qm monthly outflow, both expressed in m^3/day. The coefficient of correlation of the empirical relation is 0.82, a quite significant value.

The hydrological model and the empirical relationship between the monthly flow and overflows will be used to assess the influence of the impacts of the different scenarios (climatic, population, urban development) presented in the next paragraphs. These scenarios are applied to the model in the following ways:

a The outputs of the climatic models (daily rainfall and potential evapotranspiration) are the forcing terms of the hydrological model to simulate time series of flows and overflows;
b Changes in population result in changes in wastewater flow (Q_w) (changes in habits of water use and changes in the quantity of industrial wastewater, which we believe to be negligible, were not taken into account);
c Urban development leads to changes in: i) the territory, which is reflected in the soil drainage model, and ii) the imperviousness coefficient of the CSS (α_C) and SSS (α_s) respectively which controls both urban runoff in the CSS zone, and the infiltration of rainwater in CSS and SSS zones.

4.3. The scenarios

Combining the variables of CC, population, and urban development, the equation was made to simulate the progression of these factors over time in order to estimate results over the long term.

4.3.1. Climate-change scenarios

Three climate change data sets are used in the study, produced by an Arpege-climate atmospheric model by Météo-France (Boé, Terray, Habets, & Martin, 2006; Pagé, 2008; Pagé, Terray, & Boé, 2008; Pagé, Terray, & Boé, 2010). This data consists of a series of climatic variables (including rain intensity and evapotranspiration potential) on a spatial resolution of 50 km, calculated on a daily basis for the period of 1950-2099. Each of these three data sets starts from an initial CO_2 concentration in the atmosphere and reflects a different scenario for this concentration as defined by the Intergovernmental Panel on Climate Change: scenario B1 (very optimistic), A1B (optimistic), and A2 (pessimistic).

According to the climatic scenarios, the average annual precipitation for Nantes during the 21st century is projected to decrease by 10–20%, and evapotranspiration potential is projected to increase by 12–30%. In the future, on average, there might be less rainwater volume in Nantes.

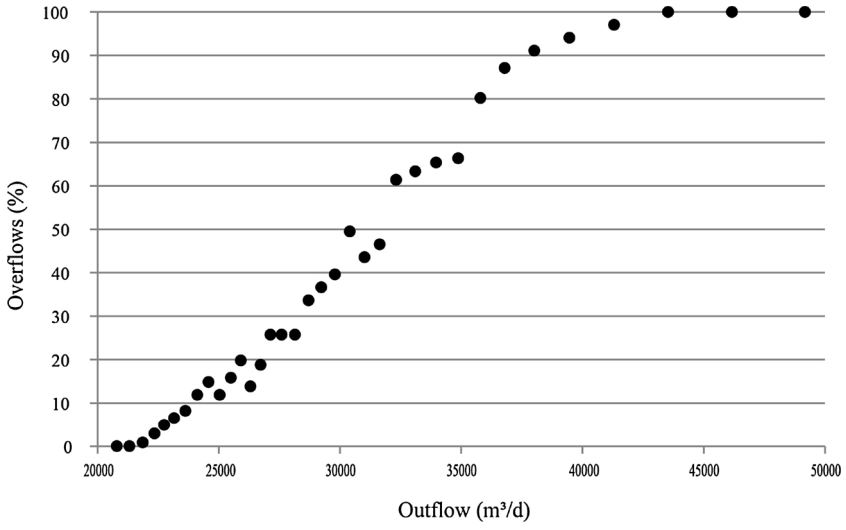


Fig. 4. Percentage of overflows which have been observed for a given total outflow.

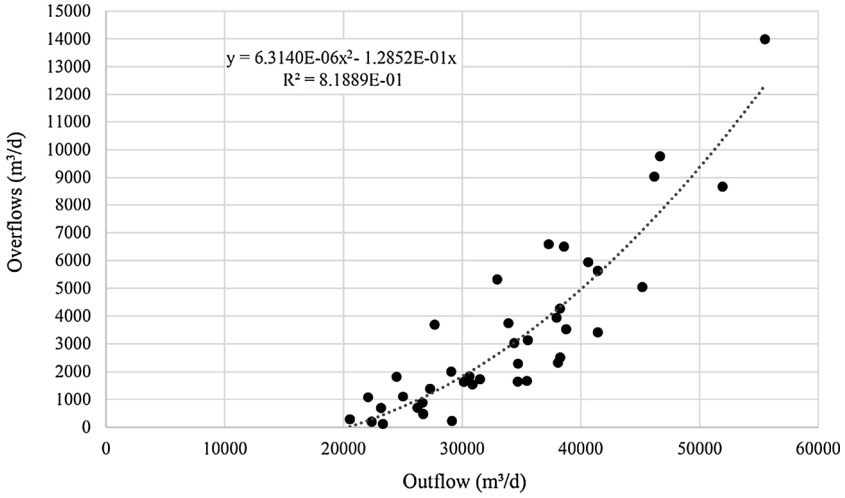


Fig. 5. Relationship between outflows and overflows.

Seven scenarios that take into account urban development and demographic evolution are described below. Each scenario is a combination of an urban-development scenario and a population scenario (urban-demographical scenario). Each urban-demographical scenario can be matched with a climate scenario. For example, urban-demographical scenario number 1 can be matched with climate scenario A1B.

4.3.2. Population scenarios

As the wastewater volume rejected per inhabitant remains constant, it is assumed in this study that variable Q_W (wastewater flow) is directly linked to the population. Hypothesizing that changes in the quantity of industrial wastewater will be negligible and that residents will not change their water use habits, we can posit that the greater the city's population, the more wastewater it produces, and therefore the greater the value of Q_W.

The population of Nantes increased by 10% from 1990 to 2000 (almost 1% per year) and the city's urbanized area doubled from 1950 to 2000 (growing at an average rate of 1.4% per year). However, this evolution is not consistent through time and throughout the urban area of Nantes. The projected rates of progression in the studied territory throughout the 21st century for these factors remain speculative.

Population growth and urbanization in the city of Nantes are expected to maintain their current rate of growth over the next decade. This study estimates that the territory analyzed in the case study is under less demographic pressure than the city center and its nearby suburbs. We can also expect for this strong rate of population growth to decline over the next century. In the case study, we divided the 21st century into two periods of 50 years, with each period using a different progression rate for each variable.

The variables for the different population and urban-development scenarios are summarized in Table 1. The two percentages indicated for each case represent the annual demographic and urbanization growth rate for the periods from 2000 to 2049 and 2050 to 2099 respectively.

The urban scenario 1 (status quo for urban and population scenario) assumes zero population growth and zero change in urban development over the next century compared to the calibration period (2004–2009). It evaluates overflows by combining this scenario with a climatic scenario. Because it simulates a complete lack of urban development, it enables researchers to measure the impact of CC independently of other factors.

Scenarios 2 and 3 assume that the population will grow, but without any additional land being used for construction. This means that scenarios 2 and 3 would involve increases in population density, so that each additional inhabitant does not occupy more land than was being used at the beginning of the century. It supposes that the additional population would live in existing buildings and/or in additional floors built above or below them. Therefore, scenarios 2 and 3 project higher population density through the addition of floors to existing buildings. The extra height of existing buildings would make it possible for the population to grow without increasing the surface area of runoff. In these scenarios, the Q_W variable (wastewater flow) progresses, while the impervious rates and the network groundwater infiltration rates remain stable.

Scenarios 2 and 3 are differentiated by their consideration of the growth rate of the population over the next century. Scenario 2 projects a large increase in the population, at a rate close to that of the beginning of this century. Scenario 3 projects a more moderate increase, at half the rate of scenario 2.

In this case study, according to existing demographic rates, we decided to increase the Q_W variable (wastewater flow) by a factor of 1% per year from 2000 to 2049, by 0.5% from 2050 to 2099 (scenario 2 for a high population growth), by a factor of 0.5% per year from 2000 to 2049, and by 0.25% from 2050 to 2099 (scenario 3 for a moderate population growth).

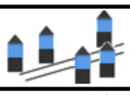
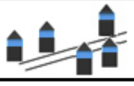
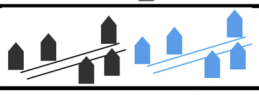
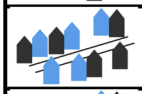
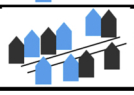
4.3.3. Urban development scenarios

The impervious rates and the network groundwater infiltration rates could be directly affected by the area's urban development. In order to accurately simulate the progression of these values, current urban- and demographic-development rates for the city of Nantes and its suburbs were used to project its development throughout the 21st century.

Scenarios 4, 5, 6 and 7 assume a moderate increase in population, as well as moderate growth of urban-development variables. Each of these scenarios considers different changes in the urban environment to accommodate the additional population. This means that, for each of these four scenarios, the parameters related to urbanization will increase along with the moderate population rate.

Scenarios 4 and 5 are designed to modify groundwater infiltration variables, unlike scenarios 6 and 7. In scenarios 4 and 5, urbanization takes place only in the SSS zone without corresponding growth in the CSS zone, which includes part of the city center and some nearby districts. These areas are older and already densely populated. Scenarios 4 and 5 differ in the rates of urbanization used: the urban-development variables of scenario 4 progress at the same rate as the population increases, while those of scenario 5 progress at half the rate of population growth. This is to simulate the different types of urban development: scenario 4 simulates the progression of urban sprawl (a "traditional" suburban sprawl development scenario), while scenario 5 projects that new urban areas will be more densely populated, with less runoff area

Table 1
Description of demographic and urban scenarios. Images in black represent the state of the population and the urban fabric at the beginning of the 21st century, and images in blue-gray represent the evolution during the 21st century. (For interpretation of the references to colour in this table, the reader is referred to the web version of this article.)

Scenarios	Demographic scenarios in sketch	Urban development scenarios in sketch
1 **Status quo** without demographic change, without urban development (except extra floor)		
2 **High population growth** without urban development (except extra floor)		
3 **Moderate population growth** without urban development (except extra floor)		
4 **Traditional suburban sprawl development** in the SSS zone with sewer system extension		
5 **Dense suburban sprawl development** in the SSS zone with sewer system extension		
6 **Densification of suburbs** in the SSS zone without sewer system extension		 in SSS zone
7 **Densification of city center** in the CSS zone without sewer system extension		 in CSS zone

and fewer new pipes per inhabitant than in a "traditional" suburban sprawl development scenario, thereby limiting per capita groundwater infiltration and rainwater runoff (a dense suburban sprawl development scenario).

Scenarios 6 and 7 assume that any new sewer construction will have no impact on groundwater infiltration in the area: either the new sewers will be perfectly leak-proof (difficult to accomplish) or no new systems will be built for new developments. For practical reasons, we believe the latter scenario to be more plausible than the former. This implies the densification of existing developments; for example, constructing a building between two existing ones and connecting it to the existing pipes. Without any extension of roads, networks, and pipes, the dynamic of exchange between the groundwater and the network remains the same. New developments would still add to runoff volumes from impervious areas, which would causes a local reduction in the proportion of rainwater reaching the ground. Scenarios 6 and 7 differ in terms of the location of this urban densification and its rate. Scenario 6 (densification of suburbs) assumes an increase of impervious area in the existing build zone served by the SSS in direct relation to the population growth rate. Scenario 7 assumes an increase in impervious area in the existing build zone served by the CSS, but at a slower pace than the population growth rate (2.5 times), because vacant land is scarce in the city center. These two scenarios are not easily comparable because they use different metrics for establishing runoff progression, and because the areas they analyze vary widely in size. A slow rate of growth of the runoff area (first 0.2%, then 0.1% per year) in the small area of the city center (4.2 km^2, 41.2% impervious) would result in a much smaller amount of new urbanized area than a larger rate of growth of the runoff area (first 0.5%, then 0.25% per year) over a much larger area (44 km^2, 28% impervious). Therefore, scenario 6 (densification of suburbs) produces 18 times more new runoff area than scenario 7 (densification of the city center) over a one hundred year period. Scenario 7 also increases the population density in the city center so that each additional inhabitant uses 2.5 times less territory on average than those who would settle in a SSS zone (scenario 6). Therefore, scenario 7 supposes, as scenario 2 and 3, a lower per capita living surface through the addition of floors to existing buildings.

5. Results

The climatic, population and urban scenarios presented in the previous sections are applied to the hydrological model to simulate time series of daily flows at the outlet of the CSS + SSS territories from 2010/01/01 to 2099/12/31. These flow time series are averaged at a monthly time step, which is used to calculate the mean overflow at this time step. These overflow values are themselves averaged over periods of 10 years. The final result serves as an indicator to assess the influence of a defined scenario on the temporal evolution of the mean overflow (expressed in m^3/day) along the nine decades ending 2019/12/31, denoted 2020, until 2099/12/31, denoted 2100, on Figs. 6 and 7. We have considered that this indicator was representative of overflowing for this case study, which was characterized by very frequent overflows, mainly caused by the intrusion of soil water into the wastewater system.

Fig. 6 presents the results of overflow simulations for the seven urban scenarios using climate scenario A1B (optimistic) to compare the impact of variables relative to demographics and urban development. Impact assessment of climate scenarios A2 (pessimistic) and B1 (very optimistic) is discussed later. Each value represents the daily average overflow volume over a ten-year period. The results show an even dispersion of values throughout the decades. However, a few clear trends are observable in the data.

5.1. Impact of climate change only: status quo scenario – scenario 1 combined with CC scenario A1B

If there is no change in the territory's population and no new development in the area, the total overflow volume from the network into the environment would decrease by a third in 100 years according to optimistic climate scenario A1B. This would be owing to decreasing groundwater-saturation levels, caused by reduced annual rainfall

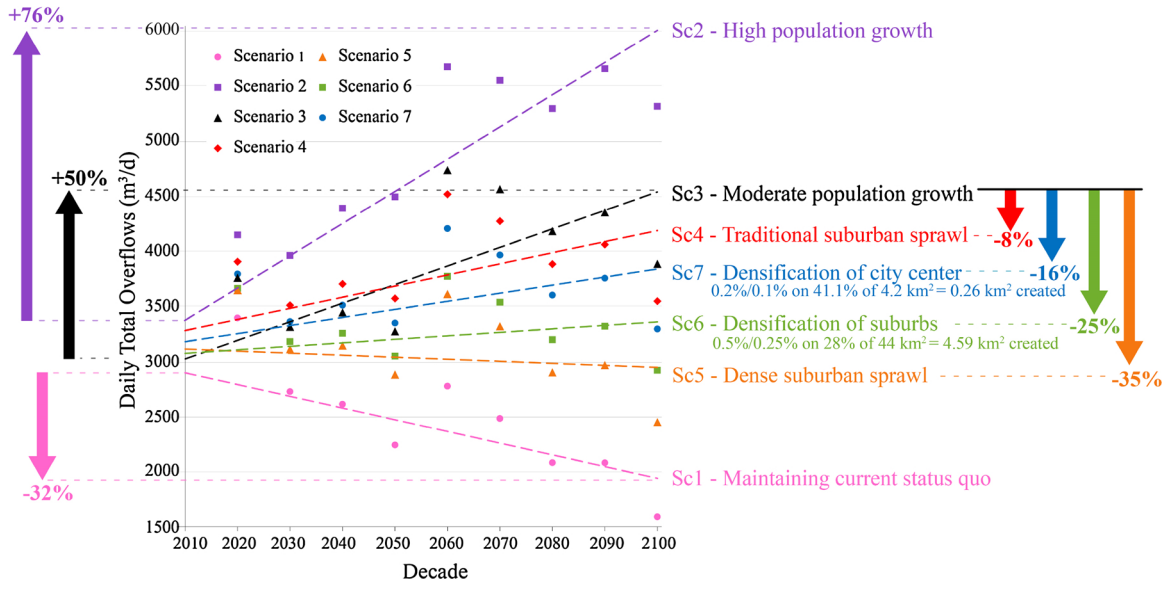


Fig. 6. Progression of total daily overflow (m^3/day) for the seven urban scenarios in the context of optimistic climate scenario A1B for the period of.2000–2100.

volumes and higher evapotranspiration. Because of lower water-table levels, groundwater infiltration into the sewer network pipes would drop and the network would not be overloaded as often by this extraneous water. The reduced value of Q_d in the equation would have a direct impact on reducing overflow. Falling precipitation rates would also have a direct effect on reducing runoff and on network overflows in rainy periods, expressed in the value Q_r.

Changes in rainfall and evapotranspiration would contribute to a significant reduction in overflow of the sewer system.

5.2. Impact of the demography – comparing urban scenarios 1, 2 and 3 combined with CC scenario A1B

Urban-demographic scenario 2 combined with CC scenario A1B shows that high population growth would increase sewer network overflow by 76% over 100 years in spite of the reductions caused by CC. Urban-demographic scenario 3 shows that more moderate population growth would increase by half sewer network overflow.

Population growth, or, more precisely, the change in wastewater volume caused by it (Q_W in the equation), is the variable with the greatest impact on overflow.

Impact of sprawling development type – comparing urban scenarios 4 and 5 combined with CC scenario A1B

Because of additional runoff surface area and sewer-system expansion, which causes an increase in groundwater infiltration, “traditional” urban sprawl mirroring the rate of population growth (scenario 4) would lead to a 27% increase (35-8%) in sewer-network overflow compared to scenario 5, which accounts for moderate urban sprawl with a higher population density. This shows that urban sprawl directly contributes to increasing sewer-network overload - thereby increasing overflow into the environment - owing to its tendency to increase groundwater infiltration volumes through network expansion. The more pipes, the greater the infiltration from the ground to the pipes, and the greater the overflows.

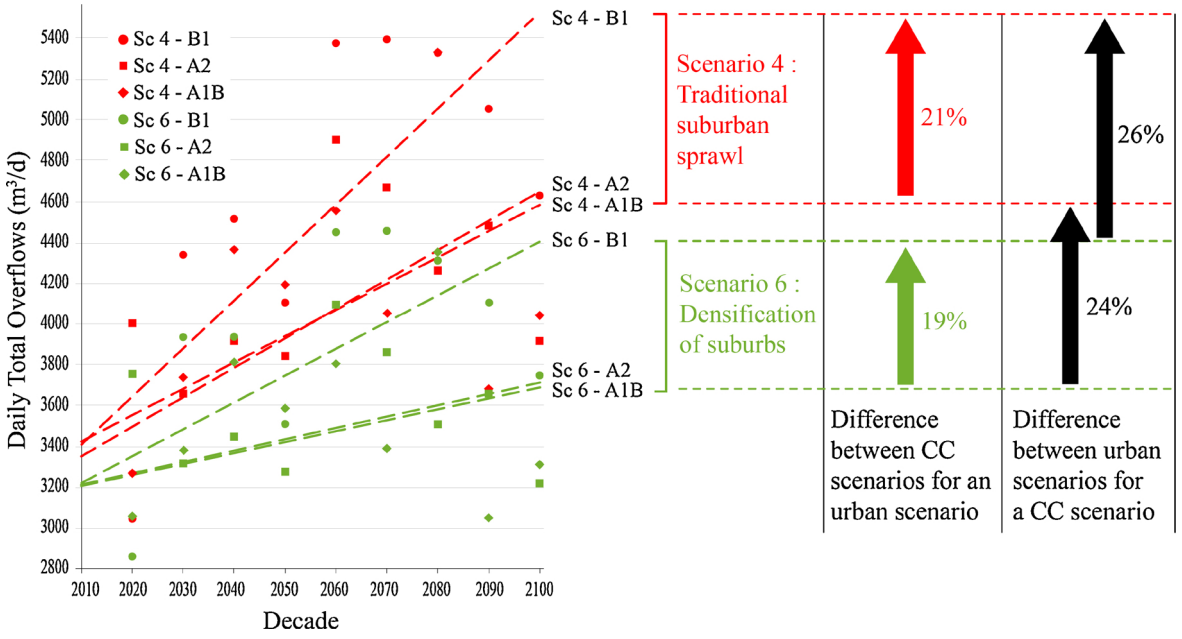


Fig. 7. Comparison of urban scenarios 4 and 6 combined with three CC scenarios.

Moderate population growth in the zone served by a SSS along with moderate urban sprawl (scenario 5) would counteract the effects of A1B scenario (optimistic) climate change, resulting in a stable rate of overflow into the environment.

5.3. Impact of urban-development type – comparing urban scenarios 4, and 6 combined with CC scenario A1B

Conversely, an urban development that densifies the existing areas (scenario 6) has a better impact than a traditional urban sprawl (scenario 4) because there is no extension of the roads and sewer networks and no additional groundwater infiltration into the pipes.

The same rate of development of runoff areas in the SSS zone, using the current sewer system without extending it (scenario 6), would reduce the overflow volumes by around 17% (25%-8%) compared to thetraditional urban sprawl (scenario 4). In the SSS zone, runoff water is collected in the separate rainwater sewer and diverted directly to the river. Increased imperviousness in the SSS zone does not contribute to a bigger charge in the main sewer. With the exception of the case of a connection error between the rainwater system and the wastewater system, the runoff water in this area would not influence wastewater overflow volumes. In addition, water from new runoff areas would flow into the rainwater catchment system instead of infiltrating into the ground.

Wherever possible, urban densification can contribute to limit overflow. It's important to note that this is only the case for zones served by SSS, and only if the extension of the sewer network is limited despite population growth and increases in runoff area.

Impact of the location of densification – comparing urban scenarios 6 and 7 combined with CC scenario A1B

These scenarios record very similar results. However, when densification is increased in the SSS zone (scenario 6), network overflow is observably less than when densification is increased in the CSS zone (scenario 7), even though scenario 6 (densification in SSS zone) produces almost 18 times more impervious area (and 18 times more housing development!) than scenario 7 (densification in CSS zone). Sewer overflow is much more sensitive to increases in the impervious area of the CSS zone than ones in the SSS zone. This is because runoff water produced by new impervious areas in the CSS zone drains directly into the combined system, causing overflow. Additional runoff into the separate system doesn't increase wastewater volume or overflow. On the contrary, rainwater infiltration into the ground is reduced, leading to a reduction in groundwater infiltration into the separate wastewater network and therefore fewer overflows.

In CSS zones, it could be advisable to use rainwater management strategies (LID, SUDS, RWH, RG, BMP) to reduce rainwater runoff, and hence diminish wastewater overflow into the environment.

Source control devices for rainwater become more and more systematic, even mandatory in some countries or regions. Rainwater source control is most often based on rainwater infiltration. In this case we have: i) increased imperviousness without reduction of infiltration (or with less reduction, if only a part of the rainwater on impervious areas is stored and infiltrated), ii) a reduction of evapotranspired volume because the surface for evapotranspiration decreases. Therefore, using this strategy could increase ground moisture level (saturation level). This increase of ground moisture would result in increased groundwater infiltration, and increased overflow. This hydrological process could be responsible for an increase in the overflow rate, rather than a decrease. This balance should be explored.

Impact of climate change scenario versus impact of urban development for scenarios 4 and 6 combined with CC scenario A1B, A2, and B1

The following figure (Fig. 7) shows the progression of total daily overflow (m^3/day) for urban scenarios 4 and 6 for the three climate scenarios (B1, A1B, A2) for the period of 2000–2100. The differences in simulation results between the most optimistic climate scenario (B1) and the most pessimistic one (A2) are similar in size or less - around 20% - to the differences in simulation results between the traditional suburban sprawl scenario (scenario 4) and the moderate urban-sprawl scenario in suburbs (scenario 6) - around 25%. The choice of CC scenario therefore does not affect the general conclusions of the research.

6. Discussion

Since it is based on climatic data collected on daily basis from regional models without additional downscaling, this modelling approach reveals average trends in overflow progression that can be compared in order to understand the relative impact of the various variables on system overflow.

Contrary to the results of most of the existing studies on the subject (Bendel et al., 2013; Denault et al., 2006; Krieger et al., 2013; Nie et al., 2009; Nilsen et al., 2011), which predict that CC will cause an increase in sewer overflow, this paper shows that, in the case of Nantes, CC will tend to reduce sewer overflow, and therefore diminish pollution of the environment. One of the reasons for this reduction in overflow is the falling ground moisture levels, which will drop as a result of the reduction of extraneous water in the sewer system. However, this decrease might cause other problems that the present study does not address.

Denault et al. (2006) and Stroch and Downes (2011) point toward urban development as the predominant factor affecting hydrological processes in the context of CC, contrary to Praskievicz and Chang (2009); Jung et al. (2010), and Tavakoli et al. (2014). The results of the present study show that man-made factors are at the origin of a significant increase in overflow and have a negative impact on the environment. This study shows that, in the case of Nantes, climate change will tend to reduce sewer overflows into the environment. Demographic growth, without a change in public water-use habits or rainwater management, is by far the most prevailing factor that we studied. It will have the greatest effect to increase the network overflows. The development of urban sprawl to accommodate population growth will have a greater impact than densification in existing residential areas. Per capita urban land use should therefore be taken into consideration, as well as changes in water-use habits and the type of sewer system used (combined or separate) in the area being developed.

The results of this research weigh the relative importance of each term of the hydrological equation in the creation of overflow volume. The wastewater flow (Q_W) is the most prevailing factor in the equation. Rainwater runoff volume (Q_r) is an important component. In this case study, the weight of this variable was relatively weak considering the small size of the CSS area that creates rainwater runoff contributing to overflows. In other contexts, the rainwater runoff volume could be a more significant factor than the others. Finally, groundwater volume (Q_d) is the less important, yet non-negligible factor that should be reduced to avoid overflows.

It is important to note the specificity of this case study, in which overflows frequently occur because of the large surface of the SSS zone connected to the CSS zone. This case is a bit different from existing studies that have examined overflows during storm events, and which are thus caused by rainwater runoff only.

This conclusion highlights the importance of measures to reduce the impact of urban development on overflow. To reduce sewer overflow in Nantes, it is advisable to: (1) reduce the volume of wastewater produced in the area; (2) reduce runoff in CSS zones; (3) increase density in existing urban zones rather than developing new ones, thus avoiding urban sprawl; (4) develop separate sewer zones rather than combined ones; (5) check pipe connections in SSS zones to avoid rainwater connection errors in the wastewater sewer system; and (6) increase population density where urban sprawl has occured.

If it is not possible to reduce population growth in the region for socio-economic reasons, it is advisable to encourage changes in resident behavior with the goal of reducing per capita wastewater production.

Urban planners should support reducing water consumption because it would have a direct impact on diminishing wastewater discharges. Possible solutions include reusing slightly dirty water before discharging it, finding alternatives to discharging wastewater (composting toilets, bio litter toilets), and developing local treatment processes adapted to reuse wastewater or discharge it into the natural environment (ground or river).

Comparison to urban sprawl, densification of inhabited spaces is a difficult endeavor. And yet sprawl is a major urban issue, both in the context of this study and in terms of sustainable city development. The results of this research clearly favor densification (in term of per-capita urban land use) as a strategy to limit overall runoff rates in the territory; in other words, it is important to create as little impervious surface area as possible and reduce their negative impact. In addition to decreasing impervious rates in new developments (parking lots, terraces, roads, etc.), new buildings and their extensions should be built to accommodate a high population density in order to reduce per capita urban land use. If densification takes place in CSS zones, it is necessary to reduce rainwater runoff flowing into the system. Rather than discharging runoff into the CSS, it could be reused for domestic purposes and/or treated to infiltrate locally into the ground (Mahaut & De Herde, 2010; Romnée, De Bondt, & Mahaut, 2014) or to flow into new urban rivers (Mahaut, 2009).

Increasing density in existing SSS zones has a smaller effect on sewer network overflow, but if nothing is done to limit runoff into the rainwater sewer system, this network might also reach its capacity and overflow, possibly causing damage to residents and the environment; this subject was beyond the scope of our research. The results highlight the importance of checking pipe connections in SSS zones to avoid accidentally diverting rainwater into the wastewater system.

7. Conclusions

7.1. Outcome

The methodology in this study involved aligning the parameters of a modelling equation that simulates wastewater overflow into the environment, taking into account demographics and urban development. The model modifies the values to simulate various climatic, demographic, and urban-development scenarios. This provides an analytical tool to illustrate the relationships between these main factors. It weighs the importance of the different variables, which allows for decision-makers to determine the pertinence of different land-development strategies. This paper quantitatively considers the causal processes for a specific element of the urban-water cycle: the overflow of wastewater into the environment. It gives an overview of the pertinence of proposed solutions to remedy the effects, while explaining the technical and natural mechanisms involved in a way that is understandable for city managers.

This study shows that the direct human impact of urban development on water management cannot be ignored. While CC will no doubt be a source of disruption in our communities, it had a smaller impact in this case study than various demographic and urban-development scenarios. Instead, CC was shown to reduce overflow volumes discharged into the environment and counteracting the negative effects of urban development in Nantes. Indeed, with no change in water use or in urban-development patterns in the city, the population growth would drastically increase overflows into the environment, whereas CC would reduce them. The progression of contemporary urban sprawl is more damaging in terms of overflows than densification. Population growth associated with contemporary urban sprawl is, without taking into account any changes in water use, the human factor shown to cause the greatest impact on overflow. The best way to limit overflow, insofar as there is no change in water use, is to densify the existing urban areas served by a separate sewer system. In combined sewer system area, the study appraises water-management practices designed to reduce overflow.

7.2. Limitation and prospects

This paper shows that the depth of the sewer network below the ground in relation to the level of the groundwater table has an important impact on the behavior of sewage overflows. While this factor is unfavorable in Nantes, where CC could contribute to reducing overflows, it could present itself differently in other cities of the world, where the interaction between the sewer and the groundwater table could be different and where CC could have other effects on the water table. Analyzing these interactions with this methodology in other case studies would make it possible to better determine the significance of these results compared to the other factors studied.

There are opportunities for further search, since this study only looked at wastewater overflow in a mixed network (combined and separated sewer system); it didn't examine the issues related to discharging rainwater from a separated sewer system into the environment, or the impact of alternative management on wastewater and rainwater.

This study focussed on a single element of the hydrological cycle of urban waters: overflows of wastewater into the environment. However, CC impacts all elements of the cycle. It would be wrong to minimize the impacts of CC based on the results of this study, which demonstrates the beneficial effects of CC solely on Nantes. For the same location, it would be relevant to measure the impact of CC on the level of the water table and the flow rates of runoff to rainwater sewer systems, especially where rainwater sewer systems are open to daylight with LID or SUDS. It would be a pity to regret the lack of water in these works made to collect rainwater. More generally, it would be useful to analyze the combined effects of CC and management on groundwater and runoff.

7.3. Implications

This paper suggests a reflection on urban water-management policies that takes into account the role of the urban-development methods used to accommodate population growth. Its conclusions can help in the elaboration of the municipal water-management plans. The results encourage municipalities to modify their urban-development practices, to initiate new densification procedures, and to encourage new management strategies for wastewater and rainwater.

This study contributes to the need for dialogue between government water and urban-planning departments, so that each party understands the effects of the decisions of one unit on the management of the other. Although this paper focuses on a specific topic (overflows from the sewer system into the environment), it deals with the general question of land- and water-management strategies to mitigate problems stemming from CC and/or population growth and/or land management itself. Beyond the question of pollution of the environment, the main issue raised in this study concerns its connection with future urban planning.

The recommendations of this paper could be challenged by the inertia of our habits, our ways of life, and our ways of inhabiting the territory. They are difficult to question when it comes to managing water, energy, or resources. But their impact on the environment can be major, in some cases much more significant than the highly publicized climate change. This paper points toward the limitations of the technical solutions envisaged as the only method of reducing overflows of waste water. A response to the limitations of our sewer networks is no longer to be found solely in technical solution but in a change in our modes of urban-development, consumption, and management of water. Indirectly, the conclusions of this research invite us to question our way of living. This research aims to help city officials prioritize actions that promote a more sustainable future and fight for a change in our ways of developing inhabited spaces in our cities and suburbs.

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